Genesis and morphological evolution of coastal talus-platforms (fajãs) with lagoons: the case study of the newly-formed Fajã dos Milagres (Corvo Island, Azores)

Carlos S. Melo[1,2,3*]; Ricardo S. Ramalho[3,4,5]; Rui Quartau[3,6]; Ana Hipólito[3,7,8]; Artur Gil[8,9]; Paulo A. Borges[8]; Frederico Cardigos[11,12]; Sérgio P. Ávila[2,8,10]; José Madeira[1,3], João L. Gaspar[7,8]

[1] Departamento de Geologia, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal

[2] CIBIO – Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado, Pólo dos Açores, Universidade dos Açores, Rua da Mãe de Deus 9500-321 Ponta Delgada, Açores, Portugal

[3] Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal

[4] School of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, Bristol, BS8 1RJ, UK

[5] Lamont-Doherty Earth Observatory at Columbia University, Comer Geochemistry Building, PO Box 1000, Palisades, NY10964-8000, USA

[6] Divisão de Geologia Marinha, Instituto Hidrográfico, Rua das Trinas, 49, 1249-093 Lisboa, Portugal

[7] IVAR – Instituto de Vulcanologia e Avaliação de Riscos, Universidade dos Açores, Rua da Mãe de Deus 9500-321 Ponta Delgada, Açores, Portugal

[8] Faculdade de Ciências e Tecnologia, Universidade dos Açores, Rua da Mãe de Deus 9500-321 Ponta Delgada, Açores, Portugal

[9] cE3C – Centre for Ecology, Evolution and Environmental Changes; Azorean Biodiversity Group; Universidade dos Açores, Rua da Mãe de Deus 9500-321 Ponta Delgada, Açores, Portugal

[10] Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre 1021/1055, 4169-007 Porto, Portugal

[11] Centro do IMAR da Universidade dos Açores, Departamento de Oceanografia e Pescas, Rua Prof. Dr. Frederico Machado, 9901-862 Horta, Açores, Portugal.

[12] OKEANOS- Research Center – Universidade dos Açores, Rua Prof. Dr. Frederico Machado, 4, 9901-862 Horta, Azores, Portugal

*Corresponding author: csmelo@fc.ul.pt (Carlos Melo)

ABSTRACT

Supratidal talus-platforms are low-relief subaerial accumulations of debris produced by mass wasting along high coastal cliffs, being particularly abundant at reefless volcanic islands subjected to high wave energy. Known as “fajãs” across the Portuguese-speaking Atlantic archipelagos, these coastal features on rare occasions may exhibit lagoons, constituting sites of high geological, biological, landscape, and social value. Whilst the origin of fajãs is firmly established as being the product of coastal landslides, little is known about the processes that shape fajãs with lagoons. In particular, doubts still remain concerning whether fajãs featuring lagoons are a fortuitous product of mass wasting, or result from marine reworking (by waves and currents) after emplacement. On October 30, 2012, a coastal landslide (~0.001 km^3) occurred on Corvo Island, Azores Archipelago, forming a nearshore gravel islet that later migrated to the island’s coast, resulting in a fajã with an ephemeral lagoon (Fajã dos Milagres). This event provided a unique opportunity to study the generation and development of fajãs with lagoons, and therefore a 3-year survey was carried out to record its evolution. This GIS-based study used aerial oblique photography and satellite optical imagery, complemented with a land survey for a more precise topographic reconstruction. Analysis of data concerning bathymetry, precipitation, and wave regime was also employed to investigate the driving forces behind the morphodynamic evolution of the deposit. “Fajã dos Milagres” evolved very rapidly, through an evolutionary pattern with five main stages: 1) “islet stage”; 2) “gravel spit stage”; 3) “early lagoon stage”; 4) “mature lagoon stage”; and 5) “fajã (without lagoon) stage”. Our reconstructions show that, for fajãs with lagoons to be formed, several factors should converge: a) presence of high coastal cliffs, made up of composite volcanic sequences, capable of producing large landslides that supply sufficient mobile sediment to the shelf; b) presence of a shallow, wide insular shelf where the sediments can be transported without significant loss to the submarine slopes; and c) a wave-dominated, high-energy regime, capable of significant cross-shore and longshore sediment drift. These observations allowed us to propose a preliminary conceptual evolutionary model for the generation of fajãs with lagoons, where marine reworking plays a fundamental role. Finally, this study documents the generation and very rapid subsequent evolution of a clastic coastal morphology solely driven by the action of waves and currents, and without interference from relative sea level and/or external sediment replenishment, with possible implications to other settings.

Key words: coastal morphology; coastal talus-platforms (fajãs); lagoons; spit bars & coastal barriers; volcanic islands; topographic reconstruction; Azores

1 INTRODUCTION

Volcanic oceanic islands are prime places to study the evolution of rocky coastlines, since these dynamic landscapes can experience very rapid changes driven by volcanism, mass wasting, strong surf, and sea-level changes (Ramalho et al., 2013). In particular, coastlines of reefless volcanic islands constitute excellent sites to study the transitional geomorphic landscapes produced by the interplay between marine erosion, mass wasting, and sediment transport, given their fast pace of evolution. In this paper, we discuss the generation and evolution of a supratidal talus-platform with an associated lagoon, a very rare clastic coastal morphology found along cliff-bounded volcanic island coastlines.

Mass wasting plays a crucial role in the evolution of volcanic island coastlines, with events ranging from large, deep-seated island flank collapses to small-scale coastal landslides and cliff failures (Ramalho et al. 2013). Although island flank collapses gave origin to some of the highest seacliffs in the world – such as those of northern Moloka’i in the Hawaiian Archipelago – they are rather infrequent at geological time scales, and tend to preferentially affect young active volcanoes at the peak of their shield-building stage (Moore et al. 1994; Carracedo, 1999; Krastel et al. 2001). Smaller scale coastal mass-wasting, on the other hand, is much more frequent, being a particularly important process at volcanic islands exposed to the highly energetic wave regimes driven by trade winds or by the strong westerlies of mid- to high latitudes. In these settings, vigorous wave erosion tends to produce steep or undercut cliffs, which are more prone to catastrophic mass movements, in contrast to other settings where weaker marine erosion and stronger weathering produce more gentle, convex coastal slopes (Emery & Khun, 1982; Porter et al., 2010; Ramalho et al. 2013). As such, in vigorous wave environments, marine erosion is generally aided by slope failure, resulting in cliff-bounded coastlines that recurrently go through cycles of marine undercutting, mass wasting of the cliff, and removal of collapsed material by waves. Such high coasts are thus subjected to recurrent local shoreline advances (when mass wasting takes place and debris accumulates at the base of cliffs) and retreats (when marine erosion removes the collapsed material), resulting in a peculiar threshold- and event-driven morphological evolution (McLean & Davidson, 1968; Noormets et al., 2002; Dickson, 2004; Ramalho et al., 2013). Coastal cliff failures are also responsible for creating large accumulations of collapsed material at the base of cliffs, which are often reworked by marine processes to create a variety of transitional morphologies, ranging from supratidal talus platforms, spit bars, and boulder and pebble beaches (Dickson, 2004; Trenhaile, 2016).

Supratidal talus-platforms are features formed by subaerial mass wasting along coastal cliffs, being more common on coastlines bound by wave-exposed seacliffs attaining several hundreds of metres in height. In the context of the Portuguese-speaking volcanic archipelagos of the Azores, Madeira, and Cabo Verde – where these features are ubiquitous – they are usually known by the term “fajãs” (singular “fajã”, Portuguese pronunciation [fɐʒɐ̃]). Fajã *s.l.* is, in fact, a term with a broader meaning, being used in the Portuguese insular lexicon to designate flat areas in the middle or base of a steep slope. These may result from landslides inside fluvial valleys, more frequently from talus accumulation or even the formation of lava deltas at the base of a seacliff. As the term fajã entered the Portuguese scientific lexicon, two main types of fajãs can be distinguished, depending on their origin: a) depositional fajãs (which can be coastal or not); and b) “lavic” fajãs i.e. composed of lava flows, typically referring to coastal lava deltas (Caniaux, 2007). Given the usefulness of a simpler, specific term, in the present work we will subsequently use the term fajã to refer to talus accumulations and more specifically concerning supratidal talus-platforms.

Coastal depositional fajãs, in more objective terms, can be defined as single or multi-generational supratidal accumulations of debris produced by small to large scale mass wasting (debris slides, rock falls, topples, and more rarely slumps), with a conical and/or fan shape, exhibiting flat or hummocky surfaces, and fringed by boulder/gravel beaches. In rare occasions they exhibit lagoons (Borges, 2003; Lameiras et al. 2009; Ramalho et al. 2013; Melo, 2015). Noteworthy examples of coastal depositional fajãs can be found along the shores of the Azores Archipelago, at Madeira and Desertas in Madeira Archipelago, on the northern shores of La Palma and La Gomera in the Canary Islands, at Santo Antão, São Nicolau, and Brava in Cabo Verde, on NW Iceland, and on the northern shore of Moloka’i in Hawaii. Coastal fajãs are sites of very high economic, agricultural, ecological, and landscape value, often constituting the only habitable (and often arable) land at low-elevations on cliff-bounded island coastlines (Borges, 2003). Moreover, coastal fajãs frequently have their own microclimate and harbour unique ecosystems, particularly in the rare occasions when they feature a lagoon. The best examples of coastal fajãs featuring lagoons include the Fajã da Caldeira de Santo

Cristo (with a tidal inlet) and Fajã dos Cubres (without tidal inlets) in São Jorge Island (Azores, see Fig.1 and Table 1), which constitute a touristic *ex libris* for which the island is famous (Borges, 2003). These fajãs were classified as UNESCO Biosphere Reserves in 2016, and were the subject of specific environmental legislation to protect their geomorphology and biological richness, among other aspects. Other, less representative examples include the smaller Fajã da Quebrada Nova dos Fenais in Flores Island (Azores) and Sítio do Lugar de Baixo in Madeira Island.

Whilst it is firmly established that coastal depositional fajãs are the product of coastal slope failures, doubts still remain on whether fajãs featuring lagoons are a fortuitous product of mass wasting or, conversely, result from coastal processes (such as marine reworking by waves and currents) after the emplacement of collapsed material at the base of a seacliff. Events at a human scale that result in the formation of fajãs are rare, and the ones generating fajãs with lagoons are even scarcer. Consequently, few observations exist that give insight on the origin of fajãs. However, during a storm in October 2012 a coastal slope failure occurred on the western shore of Corvo Island (Azores), which evolved to form a fajã with a lagoon. This event – and its subsequent morphodynamic evolution – provided a representative example for studying the generation of these landscapes. Accordingly, in the present work, we document the processes that led to the formation of a fajã with an associated lagoon. To achieve this objective, we compiled a database that included both vertical and oblique aerial photos and satellite optical imagery documenting the development of this fajã. Based on these images we obtained a time-referenced reconstruction of the main evolutionary stages that shaped this new fajã. Inferred real wave and model wave data direction during the different stages of evolution were also analysed, to investigate the role of waves in the morphodynamic evolution of the fajã. We also took into account the local bathymetry. The acquired information provides a basis to understand how mass-wasting events and subsequent marine reworking can result in such a peculiar morphology, making it possible to establish an empirical model for their origin and evolution, possibly applicable to similar fajãs with lagoons.

2 GEOGRAPHIC AND GEOLOGICAL SETTING

2.1 Azores Archipelago

The Azores is a volcanic archipelago located in the NE Atlantic Ocean, composed of nine islands roughly aligned NW-SE and younger than ~6 Ma (Ramalho et al., 2017, and references therein), and located approximately 1400 km west of Europe's mainland (Fig. 1A). The archipelago straddles an area where three major tectonic plates meet – North America, Eurasia, and Nubia – known as the Azores Triple Junction (Laughton and Whitmarsh,1974). The islands rise from a prominent bathymetric anomaly broadly defined by the -2000 m isobath, termed the Azores Plateau (Needham and Francheteau, 1974). This structure is, in general terms, bounded by the Mid-Atlantic Ridge to the west, the Terceira's Rift to the north, and the inactive East Azores Fracture Zone to the south (Searle, 1980). Whilst the majority of the islands still present active volcanic systems, two of them – Corvo (França et al., 2002) and Santa Maria (Serralheiro, 2003) (Fig. 1A) – exhibit no signs of active volcanism. Unlike Santa Maria, which is known to be uplifting (Serralheiro and Madeira, 1993; Serralheiro, 2003; Ramalho et al., 2017), there are no obvious signs of uplift on Corvo Island.

Amongst the islands that compose the Azores Archipelago, São Jorge (Fig. 1B) is the only one exhibiting large (>0.2 km^2) and stable fajãs with lagoons (Figs. 1D and 1E; Table 1). These fajãs are considered the result of a pre-settlement earthquake that produced surface rupture on the Cume da Fajã do Belo fault, triggering large-scale landslides (Madeira, 1998; Madeira & Brum da Silveira, 2003; Borges, 2003) and resulting in the formation of the two fajãs.

Corvo (Fig. 1C) is the northernmost island of the archipelago and, together with Flores Island, is located west of the Mid-Atlantic Ridge in the North American plate. Corvo can be separated into two main geomorphologic entities, which correspond to the two main volcanic units composing the island edifice (Dias, 2001; França et al., 2002): the larger Central Volcano – a 720 m-tall stratovolcano with a summit volcanic caldera –, and a younger crater row on the southern flank of the Central Volcano, from which lava flows ran down the slope to produce a coastal lava delta at the south tip of the island. An analysis on the topography and shallow bathymetry of Corvo (see Fig. 1C) suggests that the Central Volcano was originally an almost radially-symmetric edifice with ~4 km in radius (measured from the centre of the island to the shelf break at approximately -120 m). The present-day morphology of the island, however, shows a clear predominance of erosion in the W and NW sides (windward). This is clearly attested by several parameters, namely: a) the wider insular shelf in these sectors, which measures 2.5–3.0 km in contrast to 2.0, 1.0 and 1.5 km at, respectively, the northern, eastern, and southern sectors; b) the higher seacliffs along the same W and NW sectors, ranging 500–720 m of elevation, whilst on the rest of the island seacliffs range only between 150 and 190 m above sea level; and c) the distance between the central caldera rim and the coastline (notwithstanding the slight elliptical shape of the caldera), which is only 0.3–0.5 km for the W and NW sides, in contrast to 0.8–0.9, 1.3–1.8, 1.5–2.5 km at, respectively, the northern, eastern, and southern sectors. The western shore of Corvo thus features one of the highest seacliffs on the island, cut deeply in the sequence of the Central Volcano. This sequence corresponds to an alternation of weathered basaltic scoria layers, each tens of metres-thick, and basaltic subaerial lava flows generally <10 m in thickness, all dipping gently seawards.

2.2 Wave regime in the Azores

The Azores Archipelago is located in a region subjected to high wave energy, with significant waves attaining heights in winter greater than 14 m and maximum wave heights greater than 20 m (Rusu and Soares, 2012; Rusu and Onea, 2016). The insular shelves of these islands are usually narrow, so the propagation of waves to the shore is normally made without significant energy loss, and, because of wave refraction with varied bathymetry, even larger waves than in deep water can occur locally (Rusu and Soares, 2012). Wave exposure at the Azores is mainly from the NW and W, although extreme storms frequently approach from the SW (Borges, 2003; Quartau et al., 2010; 2012; Rusu and Soares, 2012; Rusu and Onea, 2016). The islands' morphology reflects the dominance of these directions, presenting higher erosional rates on the W, NW and SW coasts (windward). According to Rusu and Soares (2012) Corvo, Flores, Graciosa, and São Miguel islands do not suffer wave shadowing from other islands and thus present the highest values of wave height due to their larger fetch. Moreover, these islands to some extent act as wave barriers to the rest of the archipelago, which partially lies on their wake.

2.3 Climate

The Azores Archipelago lies on the subtropical zone of anticyclones of the northern hemisphere with its meteorological conditions being largely controlled by the Azores anticyclone (Ferreira, 1981; Santos et al., 2004). The islands are characterized by a humid temperate climate but given the variation of air temperature with altitude, the climate is cold oceanic in regions with high (>500 m) elevations, where it is excessively rainy. The mean annual rainfall at Corvo corresponds to 1145 mm. The distribution of precipitation throughout the year is uneven, with higher precipitation values recorded during the season between September and March, which is characterized by the frequent passage of depressions associated with the polar front; in the remaining months, the season is less rainy due to the influence of the Azores anticyclone. The landslide that occurred on the western shore of Corvo, on the 30th of October 2012, took place during the passage of one of those depressions, which precipitated in excess of 90 mm of rain in less than 24 h, in an otherwise relatively dry month of October (IPMA, 2012).

4 METHODS

To document the evolution of the now called Fajã dos Milagres and infer about the possible stages of evolution of fajãs with lagoons several reconstructions were made, based on remote sensing data (photos taken by locals, government officials, and visitors from various perspectives and at different moments, and satellite imagery – see Fig. 2) complemented by field campaigns. The following subsections provide more detailed information on how data was handled, and on how relevant information was extracted.

4.1 Orthorectification of oblique photographs

Our reconstructions were mainly based on photos taken by locals (Fig. 2A). Most of these correspond to oblique low-altitude aerial photos, oblique photos taken from the top of the adjacent cliff, and photos taken from offshore the collapse site. Thus, a considerable photographic record/database was compiled, from which specific photos were chosen to perform the reconstructions. To correct image deformation caused by the cameras (i.e. perspective associated with the camera orientations and lens deformation), photos were orthorectified using the "Rectify Extreme" software (http://cosmos.fc.ul.pt/downloads.html) and methodology developed by Silva (2007) and Taborda and Silva (2012). "Rectify Extreme" relies on a camera calibration technique (cf. Silva, 2007) to rectify the photos. In the cases where we did not have access to the specifications of the camera model used to take the photo, we used the specifications of a similar camera model.

4.2 Landsat imagery processing

We used Landsat imagery (Fig. 2B) to fill photo time gaps to complement the reconstructions. Landsat 7 and 8 imagery was acquired from the USGS LandSat Data Access Portal – Earth Explorer (http://earthexplorer.usgs.gov) covering the period from 1st October 2012 to 31st August 2014. Suitable Landsat images were selected manually and only those clearly showing the affected area (i.e. without clouds) were downloaded, at the L1T processing level (standard terrain correction), to ensure radiometric and geometric corrections. Both panchromatic (Band 8, high resolution image with a spatial resolution of 15 meters) and "natural colour" compositions derived from "Visible" (Blue, Green and Red) multispectral bands (medium-resolution imagery with a spatial resolution of 30 meters) of each Landsat dataset were pansharpened by using the QGIS plugin (http://planet.qgis.org/planet/tag/landsat/) (Figs. 2C and 2D). Natural colour compositions were achieved by using a 3-2-1 RGB band combination for the Landsat 7 data and a 4-3-2 RGB band combination for the Landsat 8 data (http://landsat.usgs.gov/L8_band_combos.php).

4.3 GIS reconstruction

Orthorectified photos and processed Landsat-based images were imported into ArcGIS™ software. The orthorectified photos were georeferenced using as geographical reference the 1/5000 altimetry data and the 2008 aerial photo survey (with a spatial resolution of 50 cm) produced and provided by the Azores Regional Government. At least four ground control points (GCPs) were used in each photo to achieve an accurate georeferencing. The delimitation of the fajã was performed based on the maximum observable area of the fajã taking into account wave washed areas. In total, 19 GIS reconstructions (9 based on photos; 10 based on Landsat satellite imagery) were performed.

4.4 GPS survey of the fajã

To assess the quality of the GIS reconstructions, a GPS survey was carried out during the final evolutionary stage of the new fajã, on the 19th of August 2014. We used a hand held “Garmin GPSMap 62™”, with a horizontal positioning accuracy of 3 m. Static and dynamic GPS points were collected. Comparing the GPS data with the reference points obtained through remote sensing techniques, it is possible to verify that the accuracy of the remote sensing data (13th of August 2014 Landsat 8 GIS reconstruction) was of the order of 79% for maximum length and 95% for maximum width (i.e. similarity percentage between GPS and remote sensing reconstructions).

4.5 Wave data processing

Wave data was provided by Instituto Português do Mar e da Atmosfera (IPMA), and Instituto Hidrográfico (IH). This data combines modelled wave values (ERA-Interim; geographical position N39º45’00.0” W32º52’30.0”; average distance of 149 km from western Corvo Island) and real observations from a buoy located SE of Flores Island (BOND 3; geographical position N39º21’51.6’’ W31º10’00.0’’; approximately 40 km from western Corvo Island) (Fig. 1A). The model ERA-Interim data spans 32 years (6 hours period) and the observational data 2 months (6 minutes period from 30th September 2012 to 29th November 2012). ERA-Interim data processing techniques are detailed in Dee et al. (2011) and references therein. Mean wave direction (MWD) was represented as incoming wave direction. To check for consistency, real wave direction (i.e. refracted waves as they approach the coast) was inferred from field photos and compared with the model-derived offshore directions. However, in order to perform a more realistic comparison we calculated the refraction of the ERA-

Interim waves as they approach the west coast of Corvo (see Table 2). Calculations were based on the Linear Wave theory through the equations expressed in chapter 4 of Masselink & Hughes (2003).

5 RESULTS

5.1 Wave regime

We performed a comparison between the wave direction inferred from the photos taken from the island and those given by the ERA-Interim model after modification by wave refraction on Corvo's shelf (see Table 2). Wave directions inferred from photos taken near the coast are more realistic in representing near-shore wave interaction because of the effects of shoaling such as refraction and diffraction, although being less quantitative than those given by the modified ERA-Interim model. When compared, however, the two datasets show a high degree of similarity. Only the 6th, 15th and 23rd of November 2012 and 16th of November 2013 show different incoming wave directions. This is because the mean wave direction given by the model on those days is unable to hit a coast that trends 210º. However, mean wave direction only represents the more energetic part of the ocean wave spectra. Thus, the directions that we see on the photos likely represent the second more energetic waves from the spectrum. Therefore, in our documentation of the evolution of the fajã, the wave direction inferred from the photos was chosen rather than the directions from the modified ERA-Interim model. In all other occasions, when data from photos were not available but the modified model yielded an incoming wave direction, model results were used. Given the consistency of the two datasets, we consider this to be a robust approach.

5.2 The landslide and subsequent evolution of the deposit

The landslide that originated Fajã dos Milagres occurred in an area of noticeable cliff instability (see Fig. 3A) and affected the cliff up to ~420 m in elevation (Fig. 3B–D). Observations suggest it to correspond to a debris avalanche, affecting the mid portion of an already inactive (with respect to marine erosion) sector of the western seacliff. The precise moment of the collapse is unknown since the stormy weather conditions prevented the observation of the event, which occurred on a remote zone relatively to the only settlement of the island. However, considering the precipitation and wave data, the late morning of 30th October 2012 appears to be the most plausible timing for the occurrence of the landslide; this interpretation is in general agreement with statements collected on Corvo (J. Lourenço 2014, pers. comm. 28 February) and with Cardigos (2012).

Since its formation by the end of October 2012, Fajã dos Milagres has been under constant morphological change. Effectively, in a short period of time (~2 months) the landslide deposit has evolved from a detrital islet into a fajã with an associated lagoon, followed by a later, slower evolution to its present form, without the lagoon. The deposit evolved through several distinctive morphological stages, here described in detail. The GIS reconstructions allowed estimates to be made of the maximum length, width, furthest and closest point to Corvo Island (whenever applicable), and surface area of the fajã during the entire period of evolution (see Table 3).

5.2.1 The islet stage

This stage started with the generation of a debris islet and finished with the connection of this islet to Corvo's shore (Figs. 3B-C, 4A-D, 5A-B and 6A-B). The islet was initially "C"-shaped, in plan-view and concave landward. This feature was formed on the 30th of October 2012 (according to reports from local inhabitants). However, due to the adverse climatic conditions the first photographic records date only to the 1st of November. The initial deposit (islet) is interpreted from the photographs to have been produced by the debris avalanche into the sea and its position reflects the loss of kinetic energy. The islet likely corresponds to the emerged part of a more extensive underwater debris deposit – extending well in excess of 750 m from Corvo's shore – and the greater kinetic energy in the central part of the flow is probably responsible for the "C"-shaped morphology. Figures 4B and 5A–B also show breaking waves extending ~500 m to the north side of the islet, attesting to the presence of underwater debris in this area, and suggesting that the islet is only a small portion of the total deposit. The islet's total area ranged 0.079 and 0.062 km^2, between the 1st and the 4th November 2012 (Table 3), and the deposit attained an estimated maximum elevation of ~8 m above mean sea level.

Detailed photo analysis shows that the islet was mainly composed of unconsolidated material generally finer than boulder size, i.e. mostly granules with some cobbles and small boulders, with very rare oversized boulders (see Fig. 4A–D). This grade of material is highly mobile under the action of longshore and cross-shore currents, particularly on a very energetic environment such as Corvo's.

The brownish sediment plume shown in Figs. 3B–C and 5A-D attests to the presence of a large amount of suspended sediment near shore, suggesting a continuous winnowing of the smaller grain fractions (i.e. clay, silt, and sand) during the early stages of the fajã's evolution.

A few days after emplacement, the fajã's morphology changed slightly (Fig. 5B) with the northern part of the islet becoming narrower, while the southern part widened and extended landward. Effectively, the distance between the islet and Corvo's coastline diminished over time (183 m to 119 m; Table 3), suggesting a shoreward migration of the sediments. Our observations therefore show that the coarser grain fractions migrated towards the SE, as expected due to the dominant wave regime from the WNW and NW (see Table 2). This dominant wave direction is most likely responsible for the landward strong cross-shore sediment transport leading to the subsequent formation of the gravel spit.

5.2.2 The gravel spit stage

The eastwards growth of the gravel islet continued, until the islet eventually connected to Corvo Island about 7 days after the landslide (Figs. 2A; 5C and 6C). The sediments formed a gravel spit connected to Corvo's shoreline, entering the "gravel spit stage", which lasted until the enclosing of a lagoon by the gravel spit. The precise moment for the connection between the islet and Corvo Island is uncertain, but probably occurred around the 6th of November (Figs. 2A; 3C, 5B and 6C). The connection to Corvo was sustained by sediment deposition around the eastern (shoreward) tip of the islet with some contribution from Corvo's shore, towards the islet, as suggested by the photos (Figs. 3C and 5C-D). Based on a high-quality image with low vertical distortion taken during this stage (Fig. 2A), and the most accurate available bathymetry of the studied area, it was possible to estimate a minimum total volume of the deposit of approximately 1.1×10^6 m^3 (0.001 km^3). This value was calculated using the emerged area of the spit (0.12 km^2) and the estimated thickness derived from the existing bathymetry (~20 m, based on the average shelf depth), and represents only a very coarse absolute minimum.

By the 15th of November (Fig. 5C; Fig. 6D) the gravel spit was considerably well nourished at its eastern extremity where it connected with Corvo, and had migrated landwards. On this date, the furthest point of the gravel spit was located 389 m away from Corvo's coastline. The gravel spit, therefore, migrated 290 m to the E (i.e. landwards) in 9 days and had its area reduced by 44% (Table

3). Later on the 23rd of November (Fig. 5D; Fig. 6E) the gravel spit had largely changed from the previous morphology, having adopted a more pronounced "C"-shape. This morphological change was attained essentially through a northwards growth of the northern tip of the spit, resulting in the encircling of a large bay, which had its long axis roughly oriented NE-SW.

These observations suggest that the dominant swell coming from NWW and NW (Table 2) induced the longshore and cross-shore drift of the sediments, landwards from the SE edge of the islet. As the sediments were transported into shallower depths and deposited, the available accommodation space was rapidly filled, resulting in the fast build-up of a gravel spit between the islet and the coast. As soon as the incipient spit formed (Figs. 3C, 5C–D, and 6C–E), the process accelerated, leading to the rapid widening of the foot of the spit with sediments supplied from the offshore edge of the structure. Once the gravel spit was formed, the strong alongshore sediment drift diminished, which may have led to the formation of a clockwise circulatory current inside the embayment. This, in turn, may have contributed to an increased northwards growth of the gravel spit. However, the northwards and landwards growth of the gravel spit and the gradual encroachment of the central embayment more probably rests on an inherited morphology of the underwater debris deposit, which gradually built up as breaking waves (from the NNW and NW, Table 2) pushed sediments landwards from deeper to shallower waters (Figs. 5B–D, 6C–E). Breaking waves north of the spit, during this stage, denounce the presence of underwater debris in this area, which – by inducing wave refraction – likely helped focusing sediment drift to form the barrier and close the lagoon.

5.2.3 The early lagoon stage

The onset of the "early lagoon stage" (Fig. 5E; Fig. 6F) corresponds to the moment the gravel spit almost completely encircled the central bay entailing the formation of a large coastal lagoon (480 x 219 m). During this stage the lagoon exhibited an 84 m-wide shallow-water (or tidal) inlet facing NW, which corresponds to the zone where the gravel barrier was more exposed to the dominant swell. During high tides and/or higher swell, waves overtopped the barrier crest, intermittently supplying seawater to the lagoon (Fig. 3D and 5F). It was during this stage that the lagoon attained its maximum area (0.074 km^2; Table 2), being very similar to the area of the barrier itself (0.070 km^2). Gradually, waves kept pushing the deposit landwards, with washovers (particularly during more energetic events) contributing to the sedimentary infilling of the lagoon, as well as to a progressive reduction of its size.

5.2.4 The mature lagoon stage

The moment the lagoon ceased to be visibly connected to the sea by a tidal inlet marked the onset of this stage (Fig. 5G and reconstruction of Fig. 6G). Its end corresponded to the disappearance of the lagoon, or when this feature was limited to a small, ephemeral, freshwater pond (mostly rain and spring water), located too far inland to allow wave overwash. At this stage, due to the lack of good local photo coverage, we used Landsat imagery (both Landsat 7 and 8) to produce reconstructions of the fajã (i.e. even though Figs. 5G–H correspond to photos of the mature lagoon stage, these were not of sufficient quality for GIS reconstructions, so Landsat imagery was used instead). The location uncertainty due to the pixel size is greater for the satellite images (15 m after panchromatic processing) than that of the photos taken from locals. Nevertheless, they provided robust reconstructions, due to the almost absent vertical distortion. These reconstructions show a significant reduction of the lagoon area when compared with the previous stage of evolution (see Table 3). Furthermore, this stage was also characterized by the presence of several smaller lagoons instead of a single and larger lagoon connected to the sea by a tidal inlet. The transition to this stage must have occurred sometime before the 1st of March, as suggested by satellite imagery (reconstruction of Fig. 6G). Effectively, on the 31st of March 2013, six smaller lagoons could be observed (Fig. 5G and reconstruction of Fig. 6H), with the two larger ones measuring 147 x 86 m and 118 x 53 m, respectively.

The Landsat 7 image dated of the 18th of April (reconstruction of Fig. 6I) does not show any discernible lagoon; notwithstanding this fact, we consider that the mature lagoon stage extended to a later date, given that a Landsat 7 image dated of 18th May (reconstruction of Fig. 6J) still shows small lagoons. On Landsat 8 imagery the lagoons are not identifiable (reconstruction of Fig. 6K) but a photo taken by locals on the 16th November (Fig. 5H; reconstruction of Fig. 6L) attests that the lagoons were still present albeit very reduced in size. Finally, between the 5th and the 7th of January 2014, the extratropical cyclone "Christina" (informally named "Hercules" by the media) hit Corvo Island and coincided with the complete disappearance of the lagoons (J. Lourenço 2014, pers. comm. 28

February). The disappearance of the lagoon is attributed to both sediment infilling and, more importantly, by landward migration of the deposit as the storm impacted the coastline. Hence, the mid-December Landsat 8 reconstruction (Fig. 6M) is thus still included in the “Mature lagoon stage”.

These reconstructions show that from March 2013 to January 2014 Fajã dos Milagres was generally stable, in agreement with the lower magnitude wave conditions that occurred during that period. Effectively, during this 10-month period its shape barely changed. The absence of tidal inlets suggests that any water renewal must have happened by seepage. Water renewal by overtopping of the barrier by higher-energy wave events is deemed unlikely, given the width of the barrier separating the lagoon(s) from the sea. In fact, if such extreme wave events had occurred during that period, they probably would have caused the “destruction” of the lagoons altogether, as observed later, in January 2014. During this stage, finer sediment from cliff runoff contributed to gradual infilling of the lagoons.

5.2.5 The fajã stage

After cyclone “Christina”, the lagoons practically disappeared and only traces of residual and ephemeral (possibly seasonal) lagoons/ponds were visible (Fig. 5I). The absence of permanent lagoons characterizes this last stage of evolution of Fajã dos Milagres. There are almost no photos of the fajã in the beginning of this last stage, thus reconstructions were produced from Landsat 8 imagery (reconstructions of Figs. 6N–R). A GPS survey obtained during a field campaign made on the 19th of August 2014 complemented the graphical reconstruction of the fajã during this last stage (Figs. 5J and 6S). Figs. 5K–L show a relative morphologically “stable” fajã, approximately two years after the survey.

The winter of 2013/2014 was the most energetic period since 1955 (Masselink et al., 2015). From the 5th to the 7th of January 2014 cyclone “Christina” hit the archipelago, affecting mainly Flores and Corvo. This storm, over the Atlantic Ocean, was characterized by an unusually large fetch that led to long period waves (~10 mins; Santos et al., 2014). It approached from NW and, at Corvo, attained offshore wave heights of 9–11 m. During this event, storm waves were responsible for, simultaneously, eroding the seaward margin of the fajã, and pushing the sedimentary deposit landwards, causing the disappearance of any residual lagoon. Effectively, the photos/reconstructions after this date do not show any distinct lagoon, a situation corroborated by eyewitness accounts of local inhabitants (J. Lourenço 2014, pers. comm. 19th August). After this storm, the deposit assumed a cuspate to semi-circular morphology, similar to most of the other fajãs found in the Azores. The field campaign made on August 2014, however, showed that the fajã exhibited an ephemeral pond, like the ones found at other fajãs in the archipelago (e.g. Fajã da Quebrada Nova dos Fenais at Flores Island, formed after a landslide in July 9th,1847; Silveira, 1970). This ephemeral pond, located at ± 7 m in elevation, is the result of runoff from the backcliff, as attested by the presence of runoff channels that connected directly to it (see Fig. 5J-L). This pond was still large in comparison to the size of the fajã (the pond corresponds to ~3% of the total area of the fajã, 0.002 km^2). Presently, a 30 m-wide gravel beach fringes the fajã (from low tide to storm-tide level). A significant amount of the finer debris produced by the mass-wasting event has been dispersed throughout the western coast of Corvo. The resulting sediment availability is attested by the presence of several thin sand accumulations at the base of the cliffs along the western coast.

6 DISCUSSION

6.1 Evolutionary synopsis and the role of waves

A compilation of all the reconstructions plotted in the same map (Fig. 7) shows how Fajã dos Milagres evolved during the survey period. As described above, very rapid morphosedimentary changes characterized the first 5-6 months of the evolution of Fajã dos Milagres, followed by more gradual changes after that period (Fig. 7A). The initial swift geomorphological change was caused by the energetic wave regime associated with the Azorean winter (Fig. 8). In contrast, during the following summer little change occurred (Fig. 7A–B). Once the fajã achieved a more stable morphology (mature lagoon stage), major morphological changes only occurred during storms (e.g. January 2014). This shows that, during the initial stages, morphological change occurred during fair weather conditions (albeit being very energetic), but later it was mostly driven by more extreme wave conditions. For example (Fig. 8), the most extreme event (corresponding to the “Christina”, with local wave heights of 9–11 meters) was responsible for the last major change in evolution of the fajã, resulting in the transition from the mature lagoon stage to the fajã stage. For the reasons stated above, we attribute the marked changes in the morphology of the fajã to the action of waves and wave-induced currents. The wave magnitude and direction are consistent with the observed sediment migration. It must also be noted that sediment supply from later mass wasting or longshore drift from the NW of the island was practically negligible.

Borges (2003) had already proposed the role of waves as the main factor shaping the morphology of São Jorge’s fajãs. He conducted a field test at Fajã dos Cubres (São Jorge Island), in which beach boulders from the gravel barrier were marked in order to check the coastal drift of the clasts, concluding that the predominant pattern of migration (at least on the western sector) was from W-E, in accordance with the residual longshore drift defined by Borges et al. (2002) for the archipelago.

Our observations on Corvo Island suggest that the waves swiftly grind the debris from the landslide, and that the resulting nearshore currents induced a littoral drift, which can be attested by a change of a sand-depleted W coast to a coast where an ephemeral narrow strip of sand stands at the base of the cliffs. The fajã’s exposure to the open sea along with the scarce sediment supply probably prevented the maintenance of the lagoons, leading to their infilling and to the landward migration of the whole deposit during storms.

On the western coast of Corvo, waves attain a large fetch, which contributes to the high-energy character of the coastline, even when compared to the other Azores Islands. In the case of the island of São Jorge, the fajãs with lagoons (early lagoon stage for Fajã da Caldeira de Santo Cristo and mature lagoon stage for Fajã dos Cubres, according to the classification described above) are long-lasting structures that were formed before settlement (during mid-15th century). The “stability” of these forms is interpreted to be the result of their location and higher sediment availability (Figs. 1A and 1B), and possibly also the result of their composition, which is dominated by coarser materials (i.e. mainly pebble- to boulder-sized fractions derived from lava flows). In São Jorge, the fajãs are not directly hit by the western storms, and even the north and north-western storm waves are attenuated by the shadow zone created by Graciosa Island (see Fig. 9a of Rusu and Soares, 2012). Owing to their oblique approach across the wide shelf of the island, waves at São Jorge also dissipate energy more greatly than at Corvo. Effectively, although mean wave height on both islands is just slightly higher on Corvo than in São Jorge for the summer and winter (2.0 and 3.7, and 1.9 and 3.5 m, respectively), maximum winter wave heights are significantly higher at Corvo (8.2 m) than at São Jorge (6.9 m) (Rusu and Soares, 2012). In addition, the landslides that formed São Jorge’s fajãs were probably much larger, involving significantly larger volumes of collapsed material, material that was coarser than the one observed at Corvo, as suggested by the nature of the present day deposits at São Jorge and the material outcropping in the adjacent cliffs. A much larger fajã, made up of coarser materials, inherently achieves some protection from storm overwash and the resulting sediment infilling of their inner lagoons. Notwithstanding these advantages, small geomorphological changes have also occurred on São Jorge's fajãs in the last three decades, e.g. migration of Fajã da Caldeira do Santo Cristo´s inlet, even despite stabilization attempts by the local population (Borges, 2003; Melo, 2015).

6.2 Comparison with other settings

Unfortunately, there are not many studies in the scientific literature documenting the evolution of fajãs (with or without lagoons) for a significant comparative discussion on the mechanisms and factors that concur to their evolution. Although these features are common in reefless volcanic islands exposed to high wave energy – and particularly widespread in the NE Atlantic islands – their origin and detailed evolution has seldom been described outside MSc and PhD theses (e.g., Borges, 2003; Madeira,1998, Melo; 2015) or beyond brief mentions in review papers (Caniaux, 2007; Ramalho et al. 2013). One of the few studies that address the subject concerns the talus slopes of Lord Howe Island in the northern Tasman Sea, Australia (Dickson, 2004). In this island, only cliffs higher than 200 m have talus slopes at their base, which suggests that only the higher cliffs can produce enough material by landsliding to rest a significant amount of time without being removed by marine erosion.

Notwithstanding the absence of detailed studies on the formation of fajãs, we can draw a comparison with the development of beaches on shore platforms, at least with respect to the stability of fajãs. Shore platforms have similar morphologies to shelves, but are often restricted to the intertidal zone; shelves, in simple terms, could be defined as the product of erosion of shore platforms as sea level migrates during glacial and interglacial periods (Quartau et al., 2016). According to Trenhaile (2004), beaches only develop on top of shore platforms if there is enough sediment and if beach shoreface gradient is greater than that of the platforms. During storms, fine-grained sediments easily migrate seaward and beaches are lost because their shoreface gradients become lower than that of the platform below. Therefore, only coarse-grained beaches can maintain shoreface gradients high enough to allow them to develop and persist during storms.

These two examples show that, first, enough material must be present for these features to last several years, which can only be possible (in volcanic islands without significant riverine solid discharge into the coast) through large-enough landslides affecting high cliffs. The second criterion concerns the presence of shallow and low gradient platforms for sediments to accumulate. Very steep platforms will promote the transport of sediment seaward. A third criterion is the presence of coarse-grained sediments, because finer sediments are easily lost during storms, whilst coarse-grained systems are much more resilient (Trenhaile, 2004).

6.3 Empirical model for the formation of Fajã dos Milagres

We suggest here a model for the generation of lagoons based on our observations of the geomorphological evolution of Fajã dos Milagres and existing knowledge on similar fajãs in the Azores (namely those of São Jorge). First, several pre-existing conditions appear to be required for their formation (Fig. 9):

a) High coastal cliffs of alternating layers of hard and soft materials (e.g. lava flows and scoria layers) classified as “composite coast Type II” (see Borges, 2003). These sequences provide the necessary instability for landslide generation and supply debris material with mainly gravel-sized grains. The characteristics of the mass-wasting event also play a role given that only large landslides, resulting from the collapse of significant portions of tall coastal cliffs, mobilize sufficient volume of sediments.

b) A shallow, wide and gently-dipping insular shelf where large amounts of landslide debris can accumulate and to emerge above sea level, forming islets, and subsequently be transported around without significant loss to the submarine slope of the island (Figs 9A–B). In a much steeper shelf, landslide debris would be, most likely, rapidly lost to the deeper parts of the shelf or on to the submarine slopes of the island.

c) Area exposed to a dominant incoming wave direction (e.g. windward side), where coastal erosion is more efficient, allowing the generation of high seacliffs where large landslides occur. It is also along these coastlines that energy conditions are propitious to shoreward coarse sediment transport.

The study of Fajã dos Milagres suggests that waves play a major role in the development of fajãs with lagoons, after the rapid emplacement of landslide debris into the shelf. Waves themselves, however, are also modified by the nearshore morphology including that affected by the deposit itself. Observations show that sediment migration landwards will drive the formation of a gravel-dominated barrier, allowing the enclosure of an embayment to form the lagoon, and eventually close its tidal inlet. Once without a direct connection to the sea, the characteristics of the lagoon inevitably change, given that seawater can only enter through seepage or overwash during storm events (Fig. 9C). With the infilling driven by washovers along with an important contribution of fine sediments from the backcliff runoff the lagoon gradually fills and acquires the characteristics of an ephemeral and seasonal pond. With the continued action of waves and rainwater, particularly during storms, the morphology eventually evolves to a coastal fajã without any trace of a lagoon.

The previous empirical considerations and the evolutionary stages derived from Fajã dos Milagres provide a preliminary conceptual model for the formation of fajãs with lagoons, possibly applicable to other settings. The generalization of this model, however, should be applied with care given that there are no known contemporaneous events in the same type of environment to firmly establish analogies. The observations reported in this work are, nevertheless, the first to document the evolution of a fajã with a lagoon from its generation to its demise.

7 CONCLUSIONS

Coastal landslides leading to the generation of fajãs with lagoons are uncommon worldwide. The event analysed in this study constituted an excellent opportunity to improve our scientific understanding of how fajãs with lagoons originate and evolve, and this work is the first to document the contemporaneous generation and development of a fajã with a lagoon.

We conclude that:

- Fajãs with lagoons probably are not the direct, fortuitous product of landslide events (without wave modification) but are rather coastal features that evolve by the action of waves and nearshore currents after their rapid emplacement by landslides;

- The evolution of Fajã dos Milagres suggests that fajãs with lagoons perhaps develop rapidly during their initial stages by high-energy processes, but once a certain stability is reached, more dramatic morphological changes are essentially event-driven and associated with more exceptional storms;
- The morphological evolution of Fajã dos Milagres suggest a pattern of how these coastal features may evolve, namely through the five main evolutionary stages derived in this work: “islet stage”; “gravel spit stage”; “early lagoon stage”; “mature lagoon stage”; and “fajã̃ stage”;
- Several factors probably need to converge for the generation of fajãs with lagoons to take place:

a) high coastal cliffs, made up of composite materials, potentiating the generation of large landslides that supply enough mobile material to the adjacent coast and shelf;

b) a suitable trigger event, e.g. a large storm or an earthquake to initiate the landslide;

c) a wide, shallow, and gently-dipping insular shelf, limiting the spreading of the landslide debris over a wide area and avoiding its loss down the submarine slopes of the island;

d) a highly energetic wave regime with nearshore currents capable of reshaping the landslide debris into a fajã, i.e. capable of inducing the required onshore and longshore sediment drift.

Finally, GIS reconstructions based on photos taken by locals and Landsat imagery demonstrate the reliability of this cost-free process, even in remote islands such as Corvo, that presents a cloud coverage of 70-100% during most part of the year.

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Figure 1: A) Geographic and geotectonic setting of the Azores Archipelago (modified from Lourenço et al, 1998; Madeira, 1998; Trota, 2008). NA – North American plate; Eu – Eurasian plate; Nu – Nubian (African) plate; MAR – Mid Atlantic Ridge; TR – Terceira Rift; EAFZ – East Azores Fracture Zone; GF – Gloria Fault. The black ellipse on the upper right inset represents approximately the Azores Plateau, limited by the -2000 m isobath (Needham & Francheteau, 1974). Black stars locates buoy deployed 40 km SE of Corvo Island and ERA-Interim grid node 149 km west of Corvo Island; B) Topography/bathymetry of São Jorge Island. White lines represent the -100 m and -200 m isobaths. “d” and “e” mark the places where “permanent” and “stable” fajãs with lagoons can be found in the Azores; C) Topography/bathymetry of Corvo Island. White lines represent the -100 m and -200 m isobaths. A black arrow marks the place where the 2012 event occurred; D) and E) Vertical aerial photos of Fajã dos Cubres and Fajã da Caldeira de Santo Cristo, respectively, in São Jorge Island (from Google Earth).

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between later stages (mature lagoon and Fajã stages) coincides with rougher seas (i.e. exceptional storm events).

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Table 1

Table 1 – Morphological parameters of the representative examples of fajãs with lagoons mentioned in the text.

Fajã	Maximum length (m)	Maximum width (m)	Total area (km^2)	Lagoon area (km^2)
Fajã dos Cubres (São Jorge, Azores)	400	1360	0.42	0.027
Fajã da Caldeira de Santo Cristo (São Jorge, Azores)	440	1030	0.28*	0.076*
Fajã da Quebrada Nova dos Fenais (Flores, Azores)	300	770	0.11	0.01
Fajã do Sítio do Lugar de Baixo (Madeira)	190	790	0.13*	0.003*

* The morphology of this fajã has been altered by human activity

Table 2

Table 2 – Comparison between real wave direction data (inferred from field photos), ERA-Interim wave direction data (model data), and calculated ERA-Interim wave direction data after refraction along Corvo's island shelf (modified model data; see Methods). Estimates for wave height before refraction (ERA-Interim data) are also presented.

				Real wave direction data	ERA-Interim wave direction data		ERA-Interim wave height (m)	ERA-Interim wave direction after refraction	
					Quadrants	Azimuth (degrees)		Quadrants	Azimuth (degrees)
Stage	Prior to enclosing	Islet	01-11-2012	WSW	W	261	2.79	WNW	290
			04-11-2012	NW	N	10	3.56	NW	315
		Gravel spit	06-11-2012	NNW	S	178	2.73	-Does not hit the coast	-
			15-11-2012	NNW	S	179	4.45	- Does not hit the coast	-
			23-11-2012	NW	S	182	4.58	- Does not hit the coast	-
	Lagoon	Early lagoon	04-01-2013	W	SW	235	5.00	WNW	280
		Mature lagoon	01-03-2013	-	WNW	299	3.58	WNW	300
			31-03-2013	W	W	275	4.81	WNW	289
			18-04-2013	-	NNW	333	2.46	NW	311
			18-05-2013	-	NNE	18	1.86	NW	312
			01-09-2013	-	N	351	1.38	NW	312
			16-11-2013	W	S	174	2.10	Does not hit the coast-	-
			15-12-2013	-	WNW	285	4.27	WNW	294
	Fajã	Fajã	07-01-2014	-	NW	314	6.10	NW	306
			08-05-2014	-	WSW	253	2.48	WNW	285
			24-05-2014	-	NNE	30	1.55	NW	307
			31-05-2014	-	WSW	250	2.07	WNW	285
			13-08-2014	-	WNW	303	1.87	NW	301
			19-08-2014	W	WNW	296	1.29	WNW	299

Note: in the dates for which no photos were available there is no inferred real wave data direction. Highlighted days by grey shading indicate almost or totally coincidence of inferred real and modified ERA-Interim wave direction. Some wave directions provided by the model do not hit the coast, which trends 210º.

Table 3

Table 3 – Morphological parameters measured at the different stages of evolution of the Fajã dos Milagres. Values extracted from GIS reconstructions.

Stage			Date	Maximum length (m)	Maximum width (m)	Furthest point to shore (m)	Closest point to shore (m)	Total area (km^2)	Lagoon area (km^2)
	Prior to enclosing	Islet	01-11-2012	696	214	750	183	0.079	-
			04-11-2012	732	157	677	119	0.062	-
		Gravel spit	06-11-2012	724	277	680	-	0.120	-
			15-11-2012	516	92	389	-	0.052	-
			23-11-2012	325	209	256	-	0.090	-
	Lagoon system	Early lagoon	04-01-2013	605	286	286	-	0.070	0.074*
		Mature lagoon	01-03-2013	440	230	230	-	0.087	0**
			31-03-2013	606	253	253	-	0.110	0.010
			18-04-2013	515	273	273	-	0.129	0**
			18-05-2013	616	317	317	-	0.140	0.004
			01-09-2013	488	231	231	-	0.085	0**
			16-11-2013	561	240	240	-	0.138	0.006
			15-12-2013	547	232	232	-	0.102	0**
	Fajã	Fajã	07-01-2014	546	217	217	-	0.101	-
			08-05-2014	494	229	229	-	0.098	-
			24-05-2014	550	230	230	-	0.111	-
			31-05-2014	406	178	178	-	0.060	-
			13-08-2014	445	178	178	-	0.077	-
			19-08-2014	563	188	188	-	0.071	-

Note: According to the stage of evolution some measurements do not apply. *At this stage, the lagoon was not fully closed. ** Measurement of the lagoon area was not possible, due its small size and given the lower resolution of the Landsat 7 imagery.

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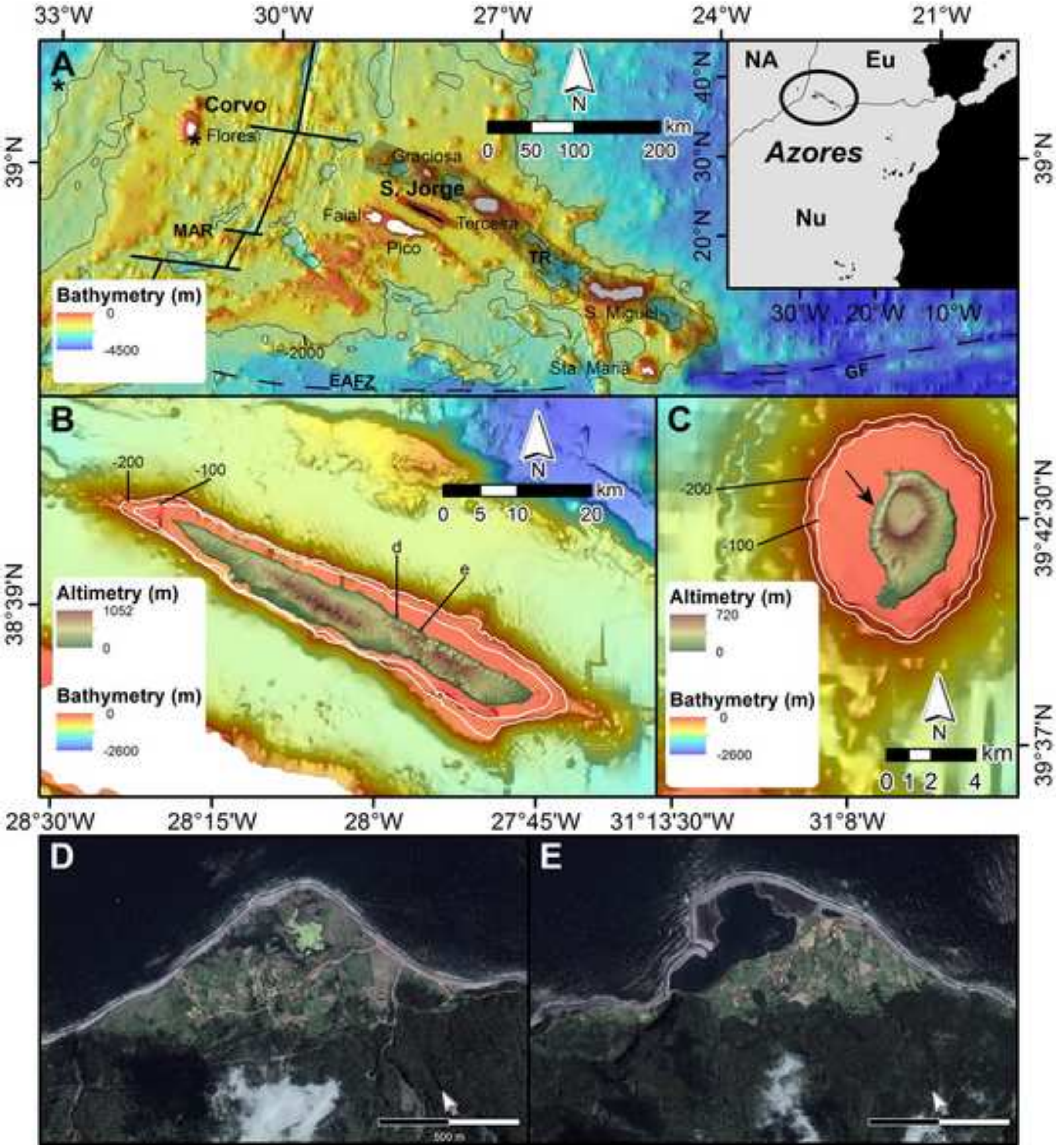

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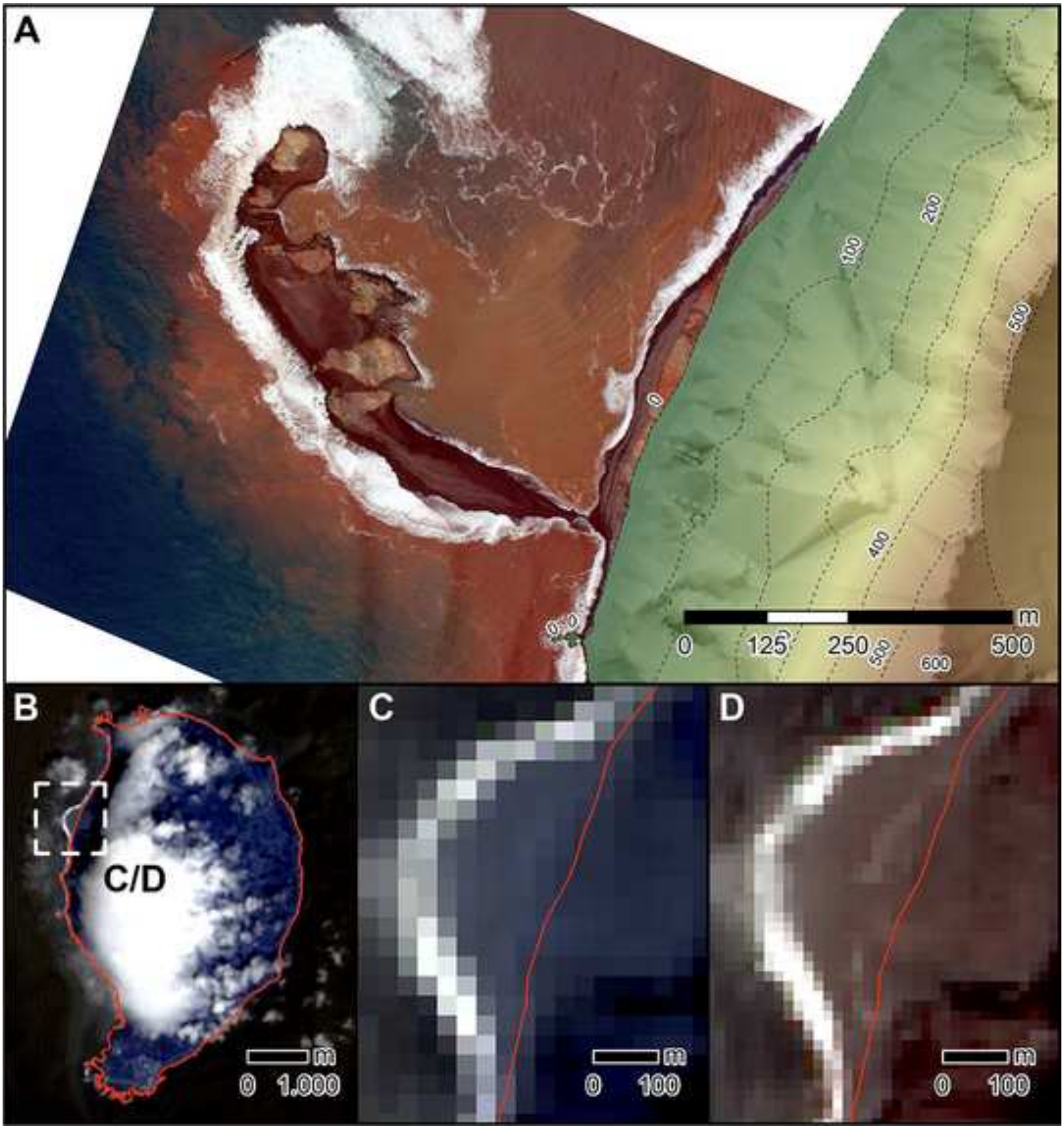

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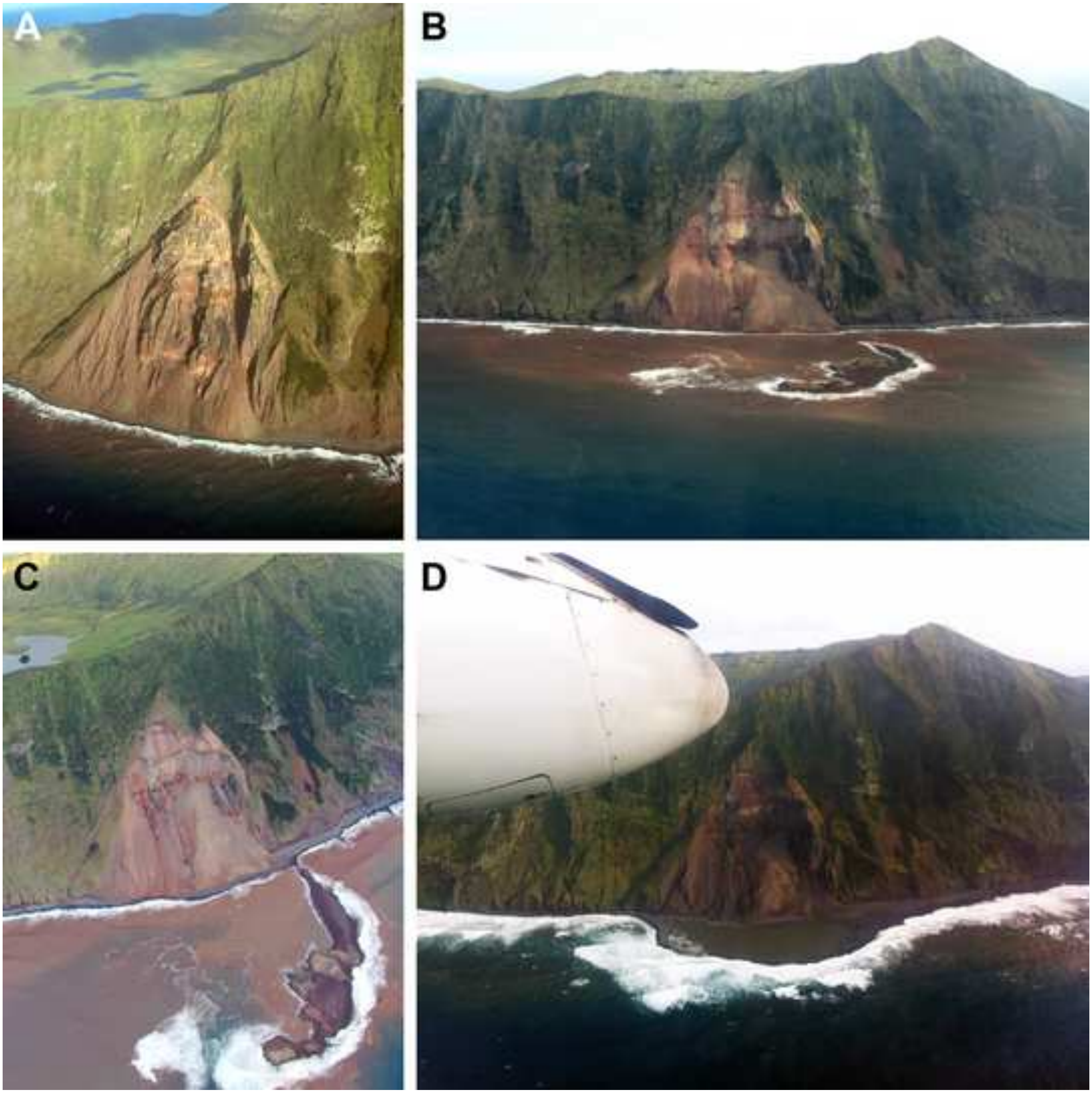

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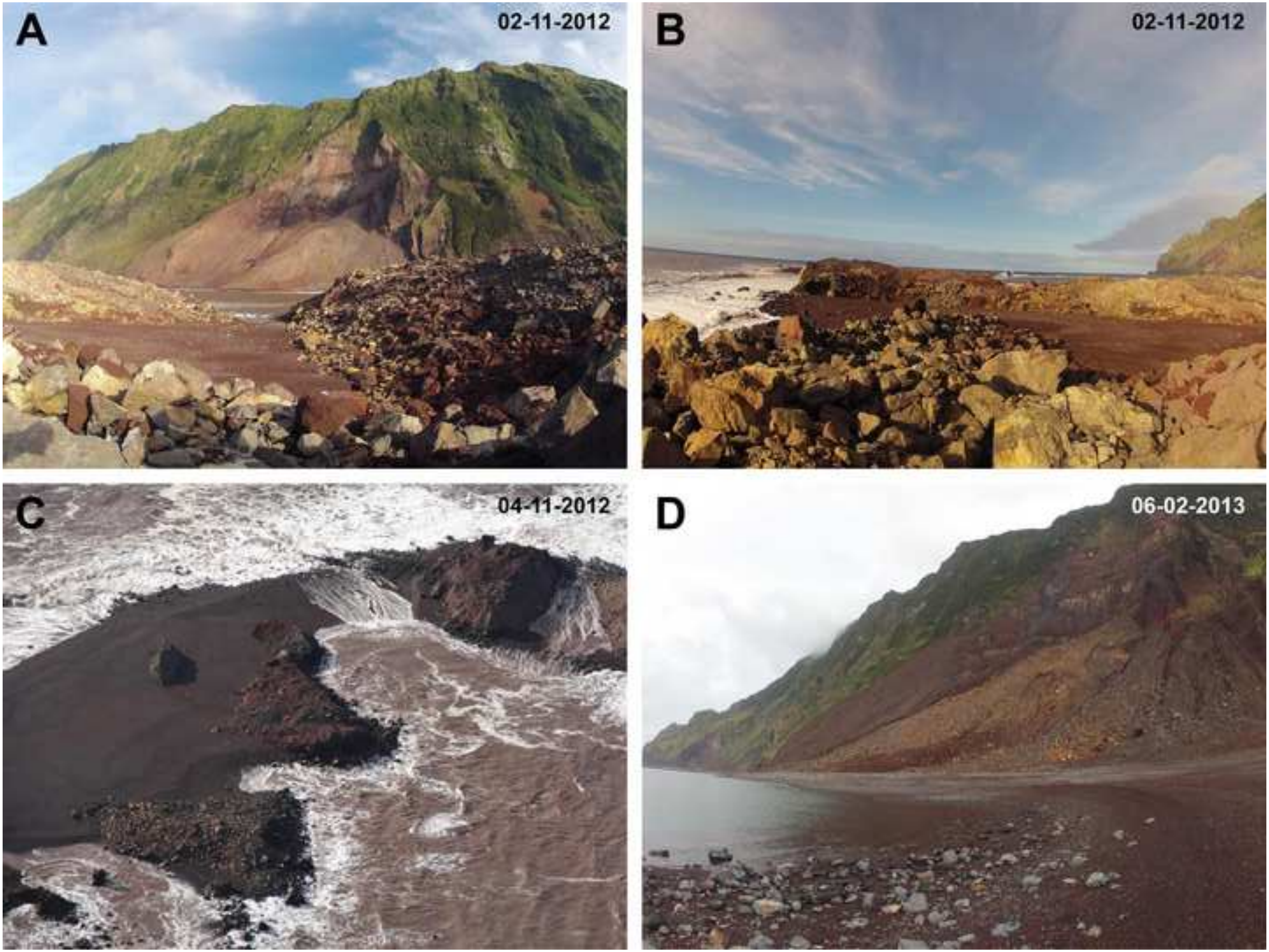

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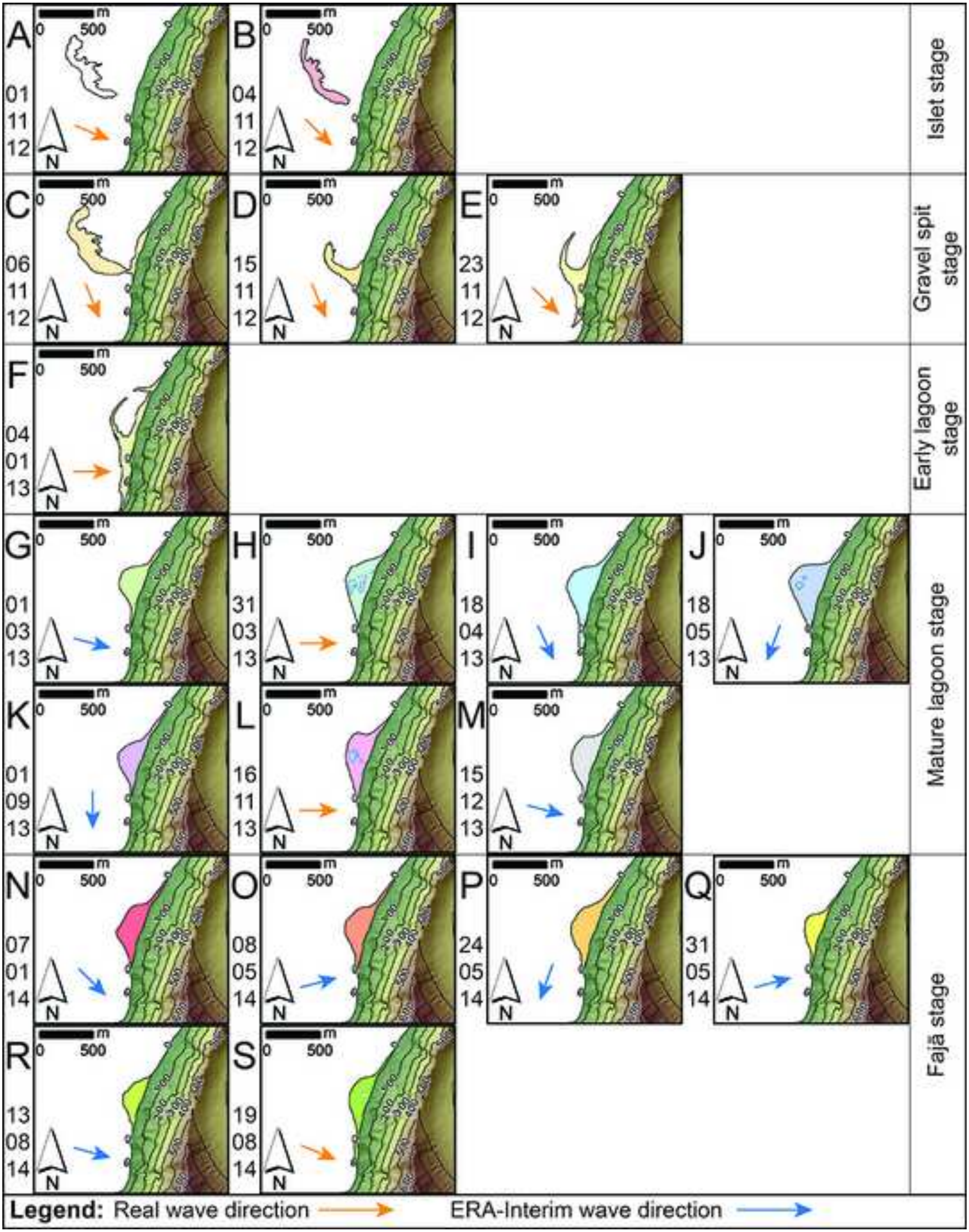

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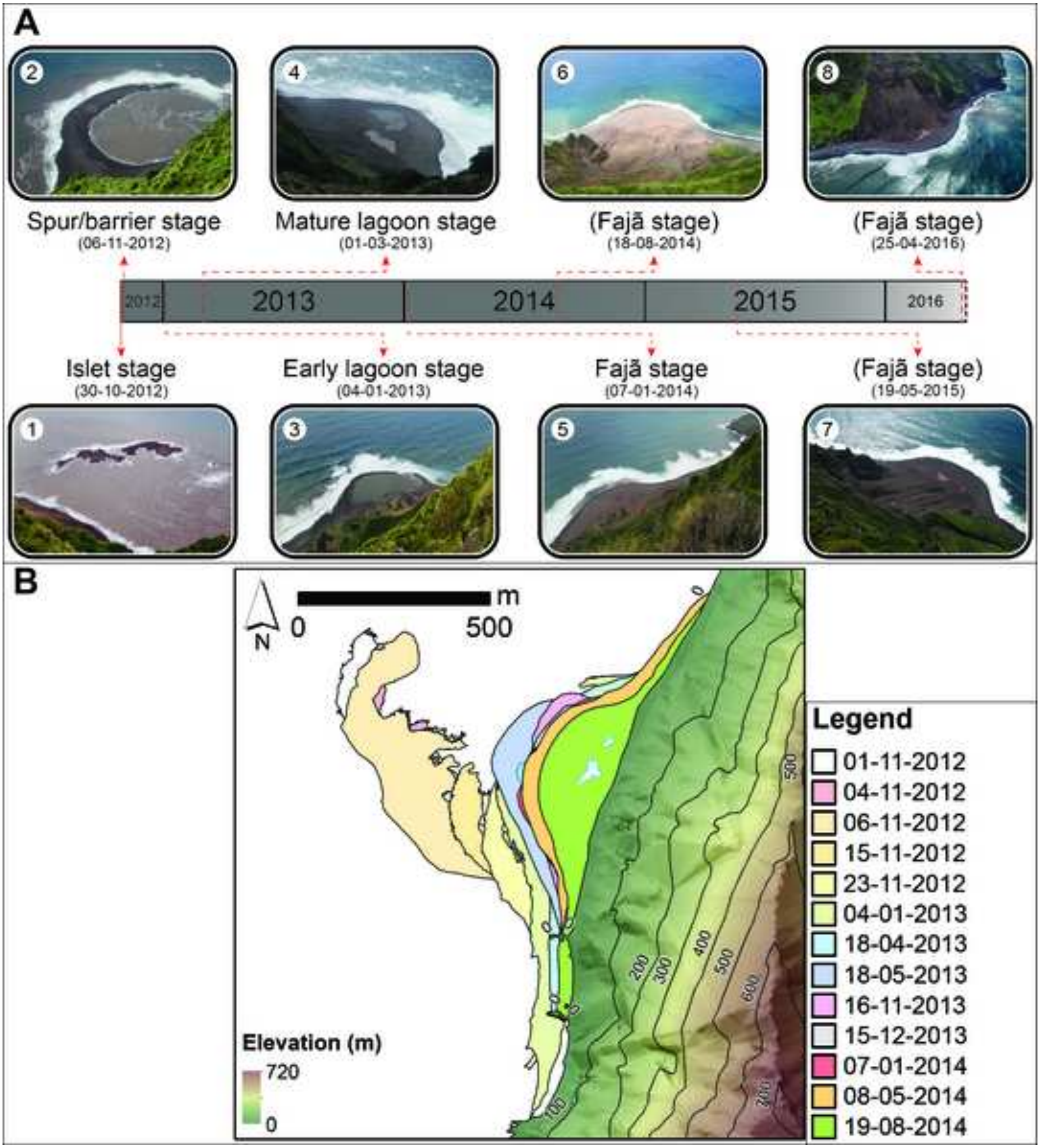

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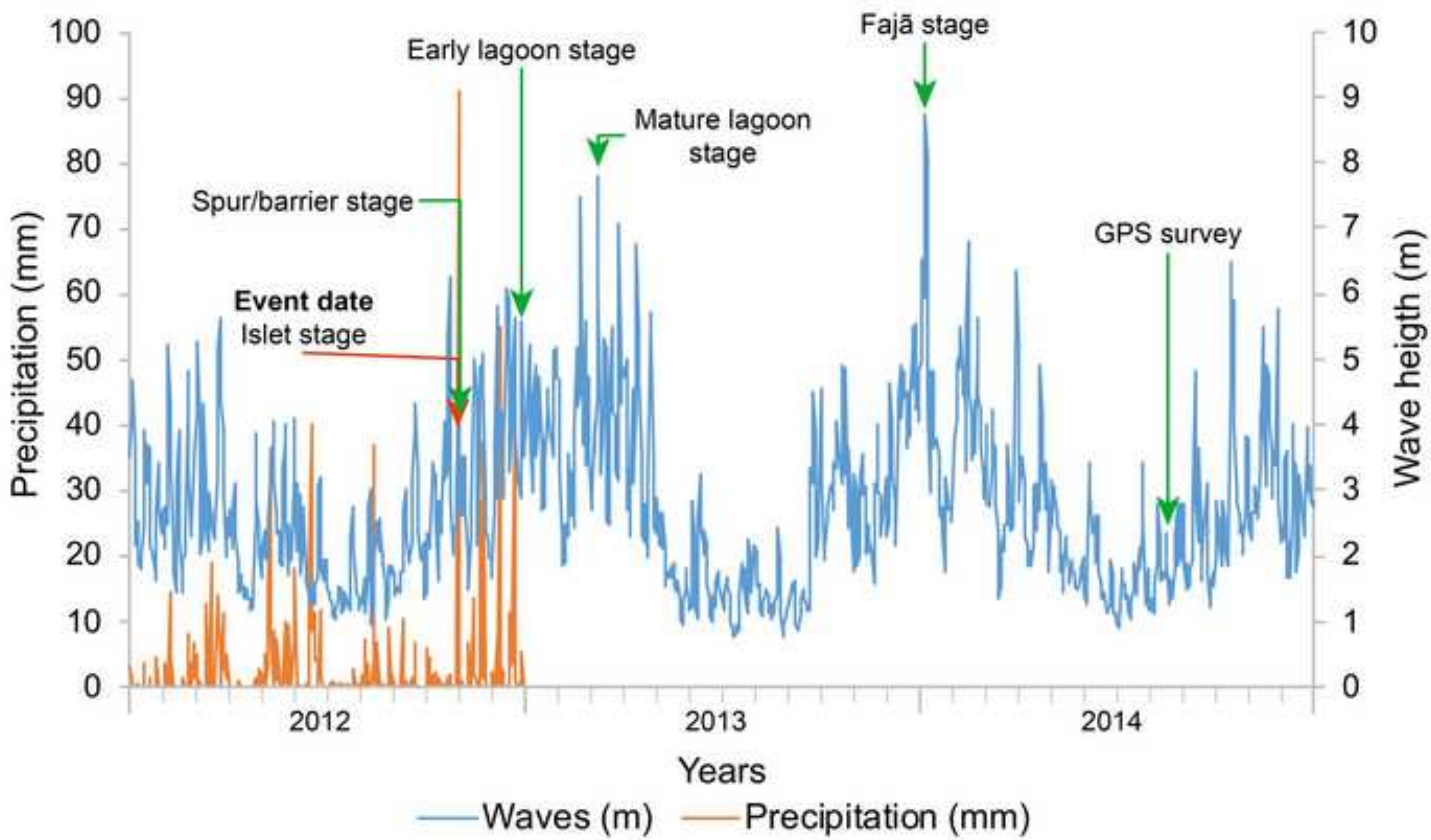

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